Renewable and Sustainable Energy Reviews 19 (2013) 565–572

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An overview on adsorption pairs for cooling

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ARTICLE INFO

Article history:
Received 18 April 2011
Received in revised form
27 October 2012
Accepted 12 November 2012
Available online 20 December 2012

Keywords:
Adsorption
Cooling
Heat pump
Working pairs
New pairs

ABSTRACT

This study is a survey for working adsorbent–refrigerant pairs and the new pairs for potential applications. The study introduces a classification for the adsorption cooling systems and a comparison between them based on the employed adsorption pairs. The comparison is on the basis of the limits of use such as coefficient of performance (COP), driving temperature, evaporation temperature and specific cooling power (SCP). The study also introduces a review of the most promising new adsorption pairs. The new pairs are introduced from the point of view of its adsorption characteristics. Finally, the study concluded that the future of adsorption cooling could be more popular as it will offer answers for the existing challenges.

Contents

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.11.037

1. Introduction

According to the increasing global energy demand, the need for renewable energy applications becomes essential. About 82% of the world's primary-energy requirements are covered by coal, natural gas, oil and uranium. Approximately 12% comes from biomass and 6% from hydroelectric power. A reduction of greenhouse gases throughout the world of about 50% is required during the next 50–100 years, according to many experts. In order to achieve this, a reduction of greenhouse gas emissions of approximately 90% per capita in the industrial countries, will be essential. Accordingly we need to change our energy supply system by drastically reducing greenhouse gas emissions [1]. To obtain this objective, solar energy utilizing will play a pivotal role.

Energy supply to refrigeration and air-conditioning systems constitutes a significant role in the world. The International Institute of Refrigeration (IIR) has estimated that approximately 15% of all electricity produced worldwide is used for refrigeration and air-conditioning processes of various kinds [1,2].

Adsorption cooling systems have received a lot of attention due to their effective cooling production using waste heat or solar energy sources. In 1848, Faraday was the first to discover vapor adsorption by using solid adsorbent. It was reported that the adsorption cycles for heat pumping or refrigeration was used in the early 1990s [3,4].

When compared with vapor compression refrigeration systems, adsorption refrigeration systems are environmentally benign and they can utilize the low-grade waste heat or renewable energy as the main driving energy and thus have a large energy saving potential.

The basic adsorption cycle for cooling consists of four processes represented in Fig. 1. A,B is an isosteric heating process. B,C is an isobaric heating process. Cooling of the adsorbent provokes a drop of pressure in the collector (process C,D). Meanwhile, the liquid refrigerant is transferred into the evaporator the adsorbent continues to decrease in temperature and pumps the liquid refrigerant, which evaporates and extracts heat from the evaporator (process D–A) generating a cooling effect [5,6].

2. Adsorbent–refrigerant pairs

The adsorbent–refrigerant pair is the vital part in an adsorption cooling cycle. The selection of any adsorbent–adsorbate pair for cooling applications depends on certain desirable characteristics of their constituents. These characteristics range from their thermodynamic and chemical properties, physical properties and additionally their costs and availability [7–9].

This study introduces a state of the art for the adsorption cooling systems. In order to choose any adsorption pair to be used in adsorption cooling applications, the present study will introduce a comparison between the adsorption cooling systems based on the assorted adsorbent–refrigerant pairs. The comparison will demonstrate the maximum coefficient of performance (COP) reached for each system and minimum delivered evaporation temperature based on the required driving source temperature. This study also introduces the new pairs which could be used in next generation adsorption cooling applications.

2.1. Physical adsorption pairs

2.1.1. Activated carbon (AC)/ammonia

Activated carbons are made by pyrolizing and carbonizing source materials, such as coal, lignite, wood, nut shells and synthetic polymers, at high temperatures (700–800 °C). Activated carbons are available in many forms including powders, microporous, granulated, molecular sieves and carbon fibers. [10].

Ammonia has a relatively high latent heat of about 1365 kJ/kg at −30 °C and the maximum adsorption quantity in activated carbon is 0.29 g/g [11], but it has the disadvantage of toxicity and corrosive. The heat of adsorption for carbon–ammonia pair is in range of 2000–2700 kJ/kg [10].

Tamainot-Telto and Criptoph [12], studied the adsorption refrigerator using monolithic carbon–ammonia pair. The results demonstrated that the maximum specific cooling power (SCP) the COP were 60 W/kg and 0.12, respectively. Tamainot-Telto et al. [13], investigated carbon/ammonia pairs for adsorption refrigeration applications. The simulation was done for 26 various AC/ammonia pairs with three cycles (single bed, two-bed and infinite number of beds) and with a driving temperature varied from 80 °C to 200 °C. Considering a two-bed cycle, the best thermal performances based on power density were obtained with the monolithic carbon, with a driving temperature of 100 °C; the cooling production was about 66 MJ/m (COP=0.45) and 151 MJ/m (COP=0.61) for ice-making and air-conditioning respectively. Critoph and Metcalf [14], reached to 0.35 COP and 2000 W/kg SCP with a plate type generator at 200 °C driving temperature and 15 °C evaporation temperature. The minimum cycle time was 1200 s.

Metcalf et al. [15], studied the optimal cycle selection in carbon/ammonia adsorption cycles. Using AC/ammonia they achieved 0.55 cooling COP at about 200 W/kg SCP in modeling results.

2.1.2. AC/methanol

AC/methanol is one of the most common working pair due to the large adsorption quantity and lower adsorption heat, which is about 1800–2000 kJ/kg. However, AC/methanol has the disadvantage of operating under sub-atmospheric pressure [10]. The maximum adsorption quantity of methanol on AC is 0.45 g/g and the latent heat at −30 °C is about 1229 kJ/kg K [13]. However, the methanol decomposes at 120 °C and aluminum alloys were found to have a stronger catalytic effect on the decomposition reaction than copper [16].

El-Sharkawy et al. [17], studied the adsorption of methanol onto carbon based adsorbents. The study presented the isothermal

Nomenclature

COP	coefficient of performance.
C	adsorption capacity of the adsorbent, (g/g).
q_{is}	isosteric heat of adsorption, (W/kg).
SCP	specific cooling power (W/kg).
T	temperature, (K).
T_{ads}	adsorption temperature, °C.
T_b	normal boiling temperature, (°C).
T_d	driving temperature, (°C).
T_e	evaporation temperature, (°C).

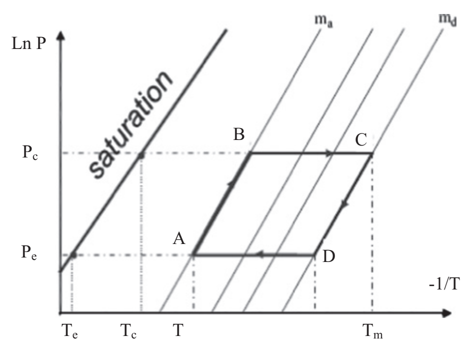

Fig. 1. Adsorption cooling in clapeyron diagram.

characteristics of methanol adsorption onto two specimens of AC. For the evaporator temperature of 15 °C, the Maxsorb III can adsorb methanol of 1.2 g/g within about 160 min. The change of SCP and COP with regeneration temperatures for various pairs (Maxsorb III/methanol, activated charcoal/methanol, LH/methanol, DEG/methanol and AC-35/methanol) was studied. The maximum COP was 0.78 with Maxsorb III/methanol at regeneration temperature of 90 °C. Theoretical results showed that the superiority of Maxsorb III/methanol pair among other carbonaceous adsorbent/methanol pairs for both of air-conditioning and ice-making applications. A system was studied by Wang et al. [18], using solidified AC as an adsorbent was had a COP of 0.125 and SCP of 16 W/kg at a cycle time of 56 min.

2.1.3. AC/ethanol

The performance of refrigeration system using AC/ethanol pair was studied by many researchers. Using highly porous AC of type Maxsorb III as an adsorbent, El-Sharkawy et al. [19] introduced a solar powered adsorption cooling system. The capacity of Maxsorb III was estimated experimentally to be 1.2 g/g with an adsorption temperature from 20 to 60 °C and the driving temperature was 80 °C. The COP of the system was about 0.8 at evaporation temperature of 15 °C. The specific cooling effect (SCE) was about 420 kJ/kg with an evaporator temperature of 7 °C.

Activated carbon fibers (ACF)/ethanol as an adsorption pair was introduced by Saha et al. [20,21]. The driving temperature was in between 60 and 95 °C. The COP reached to about 0.6 with a cycle time of 600–700 s.

2.1.4. Silica gel/water

The silica gel is a type of amorphous synthetic silica. It is a rigid, continuous net of colloidal silica, connected to very small grains of hydrated SiO_4. The pore diameters of common silica gel are 2, 3 nm (A type) and 0.7 nm (B type), and the specific surface area is about 100–1000 m^2/g [8].

Water could be considered a very good refrigerant but it has the disadvantage of impossibility to get an evaporation temperature lower than 0 °C. The heat of adsorption for silica gel/water pair is about 2800 kJ/kg [10]. One disadvantage of silica gel/water pair is the low adsorption quantity, which is about 0.2 g/g [22]. Chen et al. [23], studied experimentally a compact silica gel–water adsorption chiller without vacuum valves. Microporous silica gel with diameter from 0.5 to 1.5 mm was used. A novel heat recovery process was fulfilled after the mass recovery process to improve the COP. The cooling power and COP were 9.60 kW and 0.49 respectively when the driving temperature and chilled water outlet temperature were 82 and 12.3 °C, respectively. The optimal cycle time, mass recovery-like time and heat recovery time were 720, 80 and 20 s, respectively. Ruud et al. [24], investigated waste heat driven silica gel/water adsorption cooling in trigeneration. The system was tested as to the power delivered at 12 °C. The average cooling power was 3.6 kW with a SCP of 208 W/kg. The thermal COP, was 0.62.

Wang et al. [25], investigated the adsorption performance deterioration in silica gel/water adsorption refrigeration. It could be found that there are many factors to affect the adsorption performance of silica gel, but the pollution was the primary one to decline the adsorption capacity. In addition, the adsorption performance of the deteriorated samples after being processed by acid solution was explored in order to find the possible methods to restore its adsorption performance.

The study proved that soaking in acidic solution and washing by distilled water would be one effective method to restore the adsorption capacity of silica gel, though the silica gel must be spilled out of the adsorber.

2.1.5. Zeolite/water

Zeolite is a type of alumina silicate crystal composed of alkali or alkali soil. The porosity of the alumina silicate skeletal is between 0.2 and 0.5. There are about 40 types of natural zeolites, and the main types for adsorption refrigeration are chabazite, sodium–chabazite, cowlesite and faujasite. About 150 types of zeolites can be artificially synthesized, and they are named by one letter or a group of letters, such as type A, type X, type Y, type ZSM, etc. Artificially synthesized zeolite molecular sieves have micropores with uniform size, and different sizes can be obtained by different manufacturing methods. 4A, 5A, 10 × and 13 × zeolite molecular sieves are the main types used for adsorption refrigeration. The desorption temperature of zeolite pairs is about 250–300 °C [10]. The heat of adsorption for the Zeolite/water is in range of 330–4200 kJ/kg whoever; natural zeolites have lower values than synthetic zeolites [22]. The maximum amount of water could be adsorbed by zeolite were estimated by Ismail et al. [26] to be 0.12 g/g using zeolite 13 ×.

Wang et al. [27], investigated design and performance prediction of a novel zeolite/water adsorption air conditioner. The conditioner supplied 8–12 °C chilled water for the fan coil when it was driven by 350–450 °C exhaust gas. The designed refrigerating power and COP were 5 kW and 0.25 respectively. The refrigerating power of the machine was up to 10 kW with an evaporating temperature of 6.5 °C. The cycle time was 1320 s and the SCP reached to 200 W/kg. Vasta et al. [28], developed a mobile adsorption air conditioner employing zeolite/water pair. By using

a double adsorption bed, the COP of the system was about 0.4 whereas the SCP was about 600 W/kg.

2.2. Chemical adsorption pairs

The thermo-chemical refrigeration type offers some advantages with regard to the conventional systems as: low temperatures and dissociation pressures, adsorbent vapor rectification is not necessary and it is possible to be cooled by air. Their main disadvantages are the intermittent operation and the low thermal conductivity of the solids [29].

2.2.1. Metal chlorides/ammonia

The metal chlorides for adsorption refrigeration are mainly calcium chloride, strontium chloride, magnesium chloride, barium chloride and nickel chloride [29]. The disadvantage of metal chlorides/ammonia as working pair is mainly related to the salt swelling and agglomeration during adsorption, which compromise the heat and mass transfer [22].

Duenas et al. [30], introduced a dynamic study of the thermal behavior of solar thermo-chemical refrigerator: barium chloride/ ammonia for ice production and the COP were about 0.63. The evaporation temperature was $-10\,^{\circ}C$ and the driving temperature was decreased to 52 °C.

2.2.2. Metal hydrides/Hydrogen

When hydrogen is adsorbed by a hydride, an exothermic reaction occurs and heat is liberated. When hydrogen gas is desorbed from a hydride, an endothermic reaction occurs, providing significant cooling. There are 26 known adsorbed metal hydrides for hydrogen [31].

Metal hydrides offer a wide range of potential applications because the existence of hydrides with equilibrium temperatures (for 1 bar equilibrium pressure) between $-113\,^{\circ}C$ and 527 °C and above. The disadvantage of the metal hydrides/hydrogen is the weight of the system, which is nearly twice as high as for a system working with evaporator and condenser.

Three different schemes of metal hydride adsorption cooling applications were presented and compared based on theoretical evaluations. The single and double stage devices showed reasonable performances. Cycle times of about 300–600 s could be obtained with these devices. This SCP was about 100–200 W/kg for single stage or 150–300 W/kg for double stage. The maximum COP of a metal hydride/hydrogen cooling system were 0.83 with an evaporation temperature of 3 °C. The driving temperature was 85–215 °C whoever; the minimum evaporation temperature could be $-50\,^{\circ}C$ [32]. The maximum amount of hydrogen which could be adsorbed in metal hydrides (MgH_2) is 0.073 g/g at 0.6 bar pressure [33].

2.2.3. Metal oxides/water

An example for the metal oxides and water in refrigeration is the reaction between magnesium oxide and water [34].

Kato et al. [35], reported that the hydration resulted at an evaporation temperature of 100 °C with a driving temperature of 200–300 °C and a vapor Pressure of 101 kPa. The total time of the cycle was about 240 min.

2.3. Composite adsorbents

The first reason to improve heat and mass transfer performance of chemical adsorbents is to increase the performance of the adsorption process. Salt swelling reduces the heat transfer, and salt agglomeration reduces the mass transfer. Therefore, the addition of chemical adsorbents such as expanded graphite which have a porous structure and high thermal conductivity to a metallic salt will help to raise the heat transfer performance [36,37]. The second reason to use additions to the chemical adsorbents is a trial to increase its permeability [38]. The composite adsorbents made from porous media and chemical sorbents are commonly a combination of metal chlorides and AC, or ACF, or expanded graphite, or silica gel or zeolite [22].

2.3.1. Silica gel and chlorides/water

Aristov et al. [38], tested $CaCl_2$ and LiBr with a different micro and mesopores of silica gel as an adsorbent and water as an adsorbate to introduce a new composite adsorption cooling pair. The results showed that the water adsorption capacity could be reached to 0.75 g/g. The desorption temperature was 70–120 °C and the maximum pressure was about 10 kPa and the minimum pressure of the adsorption cycle was 1 kPa. The evaporation temperature was 7 °C with a COP in range of 0.8.

2.3.2. Silica gel and chlorides/methanol

The capacity of silica gel and chlorides to methanol adsorption could be reached to 0.8 g/g [39]. Maggio et al. [40], introduced a simulation of solid adsorption ice-maker using a composite adsorption pair of lithium chloride and silica gel/methanol. The results showed that the maximum COP of 0.33 and the maximum daily ice production of 20 kg/m^2 could be obtained. The lowest evaporation temperature was $-10\,^{\circ}C$ and the driving temperature was in range of 47–57 °C. The maximum adsorption cycle pressure was about 20 kPa and the minimum pressure was about 3.5 kPa and the cycle time was 24 h.

2.3.3. Chlorides and porous media/ammonia

Oliveira et al. [41], evaluated the cooling performance of a consolidated expanded graphite calcium chloride reactive bed. SCP was higher than 1000 W/kg and COP was about 0.35. The capacity of the bed was 0.8 g/g and the cycle time was about 5 min. The evaporation temperature was between -20 and $-30\,^{\circ}C$ and the driving temperature was about 150 °C.

A lab scale adsorption chiller worked using a porous matrix modified by active salt as an adsorbent and ammonia as an adsorption pair was introduced. Composite material (45 wt% $BaCl_2$/vermiculite) could provide effective operation of the chiller using a low potential heat source of 80–90 °C to obtain a COP value of about 0.54 and SCP ranging from 300 to 680 W/kg. The evaporation temperature was 10 °C and the time of the cycle was in range 360–720 s. Maximum and minimum pressures of the cycle were 15 bar and 5 bar respectively while, the maximum adsorption capacity was about 0.239 kg/kg [42,43].

A novel adsorbent of ammonia based on binary salt system $BaCl_2+BaBr_2$ inside vermiculite pores was designed for adsorption cooling cycle by Grekova et al. [44]. The dynamics of ammonia adsorption on the composite was studied by a Large Temperature Jump method under working conditions of the cycle. The maximum SCP of the cycle was estimated as 1200 W/kg.

The performance of an ice-maker using composite adsorbents made by the $CaCl_2$ and AC, were researched by Wang et al. [45]. AC was used as a type of porous additive, where a mass ratio between $CaCl_2$ and AC was 4:1. The ice-maker showed a COP and a SCP of 0.35 and 493.2 W/kg respectively with a cycle time of 50 min. The evaporation temperature was about $-15\,^{\circ}C$ and the desorption temperature was about 117.5 °C.

2.3.4. Zeolite and foam aluminum/water

The performance of the adsorption refrigeration system works with a composite zeolite and foam aluminum/water as an adsorption pair was studied by Hu et al. [46]. The calculations

showed that, at 250 °C driving temperature and 10 °C evaporation temperature the COP could be 0.55. The SCP could be reached to 500 W/kg with a cycle time of 20 min and the maximum adsorption capacity was about 0.22 g/g.

3. Comparison between working pairs

In order to clarify the current situation of the adsorption pairs a comparison between working pairs has been conducted. Table 1 introduces a comparison between the adsorption working pairs based on COP, SCP, delivered evaporation temperature and required driving source temperature. The comparison covers existing systems. This information can be used particularly for a specific requirement.

Fig. 2 shows the COP of the adsorption cooling systems based on the adsorption pairs. it is clear from the figure that the maximum COP could be obtained is 0.83 which achieved by using by employing metal hydrides/hydrogen pair. The highest COP values could be considered by using AC/methanol, AC/ethanol, metal hydrides/hydrogen and silica gel and chlorides/water pairs. The heights SCP could be achieved by the adsorption cooling system which has AC/ammonia pair. Figs. 3 and 4.

From Table 1, it is obvious that most of the adsorption cooling systems are good to be driven by a low-grade heat source temperature lower than 100 °C. The lowest driving temperature is 47 °C which could drive the system of silica gel and chlorides/methanol pair. According to the evaporator temperature, the lowest evaporator temperature is −50 °C which could be produced by the system of metal hydrides/hydrogen pair. This because that the hydrogen has a very low normal boiling temperature (−252.87 °C).

It is clear that there is no ideal working pair for adsorption cooling applications, but every system has an advantage over the others. So in order to choose the best appropriate system, the application should be determined accurately. One can choose the adsorption pair from the point of interest as low evaporator temperature or low driving temperature or high SCP or high COP.

4. New adsorption pairs

Accordingly, newly developed adsorbent–refrigerant pairs are also presented to attain optimized adsorption working system. For next generation adsorption cooling application, AC/hydrogen, zeolite/CO_2, zeolite/N_2, ACF/N_2, AC/N_2, AC/diethyl ether, AC/R134a, AC/R507a, AC/n-butane and AC/CO_2 pairs are presented.

4.1. AC/hydrogen

The characteristics of hydrogen adsorption on AC were experimentally studied by Huang et al. [47], Kojima et al. [48]. The conventional AC, graphite nanofiber and single walled carbon nanotube, Litchi trunk was activated by potassium hydroxide under N_2 or CO_2 atmosphere. Nanoparticles of palladium were impregnated in the prepared AC. The maximum hydrogen adsorption capacity was 0.0289 g/g at −196 °C under 0.1 MPa. With 10% palladium the adsorbent capacity of hydrogen could be reached to 0.055 g/g under a pressure up to 6 MPa at 30 °C. The isosteric heat was in a range of 5.6–7.9 kJ/mol for the adsorption pair at −196 to −183 °C.

4.2. Zeolite/CO_2

The thermodynamic adsorption properties of CO_2 with zeolite were studied by Ridha and Webley [49]. Potassium chabazite (KCHA), sodium–chabazite (NaCHA) and lithium-chabazite (LiCHA) powders were used to estimate the optimum conditions for CO_2

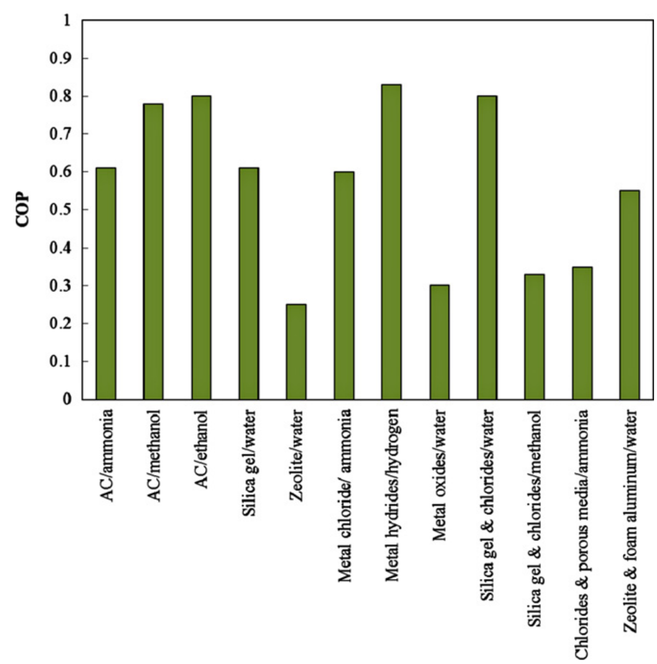

Fig. 2. COP of the various adsorption cooling systems based on the working adsorption pairs.

Table 1
Comparison between the adsorption working pairs.

	Working pair	COP	SCP	T_e	T_d
			W/kg	°C	°C
Physical adsorbent	AC/ammonia [10–15]	0.61	2000	−5	100
	AC/methanol [16–18]	0.78	16	15	90
	AC/ethanol [19–21]	0.8	N.A	3	80
	Silica gel/water [22–25]	0.61	208	12	82
	Zeolite/water [26–28]	0.4	600	6.5	350
Chemical adsorbent	Metal chloride/ ammonia [29,30]	0.6	N.A	−10	52
	Metal hydrides/hydrogen [31–33]	0.83	300	−50	85
	Metal oxides/water [34,35]	N.A	78	100	200
Composite adsorbents	Silica gel and chlorides/water [38]	0.8	N.A	7	70
	Silica gel and chlorides/methanol [39,40]	0.33	N.A	−10	47
	Chlorides and porous media/ammonia [41–45]	0.35	1200	−15	117.5
	Zeolite and foam aluminum/water [46]	0.55	500	10	250

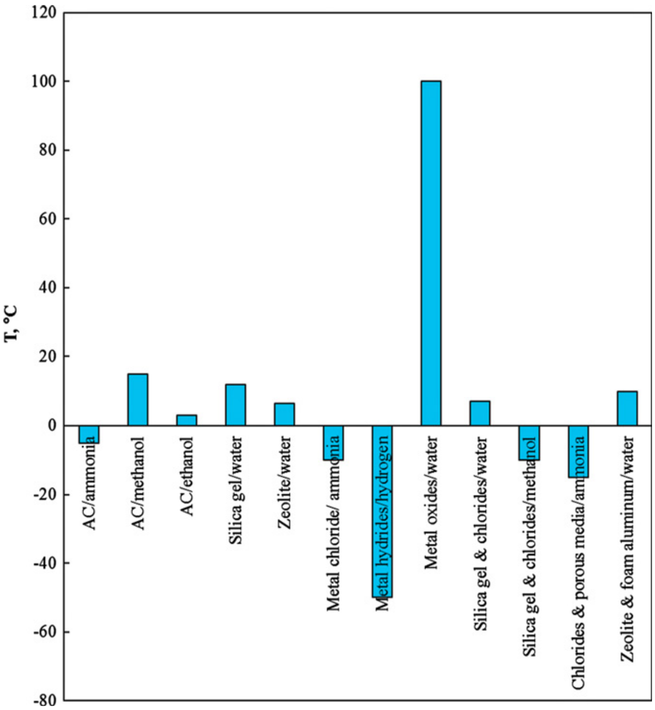

Fig. 3. Evaporator temperatures for the various adsorption cooling systems based on the working adsorption pairs.

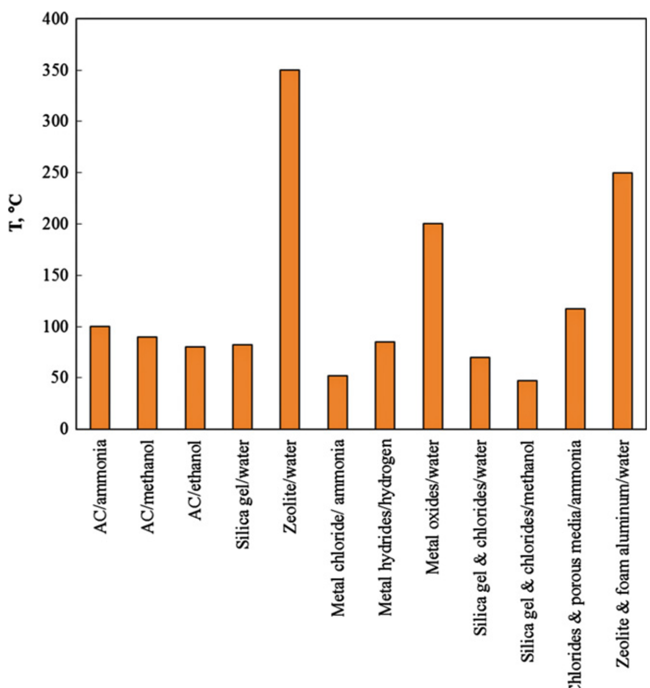

Fig. 4. Driving temperatures of the various adsorption cooling systems based on the working adsorption pairs.

adsorption. The LiCHA introduced the best results according to the other adsorbents according to the adsorption capacity. The adsorption capacity of CO_2 in LiCHA could be reached to about 0.27 g/g under a pressure of 100 kPa and at a 0 °C and it was 0.24 g/g for NaCHA.

The isosteric heat was the lowest magnitude with NaCHA as it was 40.8 kJ/mol where, it was about 43.5 kJ/mol with LiCHA for the temperature of 0 °C. The evaporation temperature of CO_2 is −78.51 °C. Zhong et al. [50] introduced a theoretical model for CO_2 as a refrigerant with some adsorbent. The model calculated the COP of the adsorption system. The COP of the adsorption system employing zeolite/CO_2 was very low as it was about 0.044 with a 200 °C driving temperature and −5 °C evaporating temperature.

Table 2
Characteristics of the new adsorption pairs.

Adsorption pair	q_{st}	C	T_{ads}	P	T_b	t
	kJ/kg	g/g	°C	kPa	°C	s
AC/hydrogen [47,48]	2800	0.055	30	6000	−252.87	N.A
Zeolite/CO_2 [49,50]	988.64	0.27	0	100	−78.51	N.A
Zeolite/N_2 [49]	435.7	0.04	0	100	−195.8	N.A
ACF/N_2 [51]	417.9	0.8	−196	N.A	−195.8	N.A
AC/N_2 [52]	625	0.00756	30	100	−195.8	N.A
AC/Diethyl ether [53]	619.5	1.63	35	10	34.45	1200
AC/R134a [54–56]	205.82	2	30	800	−26.55	1200
AC/R507a [55]	N.A	1.3	20	N.A	−47.1	1100
AC/n-butane [57]	406	0.8	25	232.3	−0.55	1400
AC/CO_2 [58]	526.6	0.0844	30	100	−78.51	N.A

4.3. Zeolite/N_2

According to Ridha and Webley [49], nitrogen has the ability to be adsorbed by zeolite. As the normal boiling temperature of nitrogen is −195.8 °C it can be considered as a refrigerant. The characteristics of adsorption of zeolite with nitrogen were introduced. The adsorption capacity of chabazite was 0.04 g/g under a pressure of 100 kPa and 0 °C. The isosteric heat was decreased to 12.2 kJ/mol.

4.4. Activated carbon fibers (ACF)/N_2

A pair of Iodine doped ACF heated at 673 K for 2 h as an adsorbent and nitrogen as an adsorbate was studied by Yang and Kaneko [51] to estimate its adsorption characteristics. The adsorption capacity of nitrogen was found to be about 0.75 g/g at −196 °C. The isosteric heat was to be about 11.7 kJ/mol. Activated carbon fibers without Iodine was also studied with nitrogen as an adsorption pair. The results for ACF without Iodine showed the same amount of isosteric heat and more adsorption capacity than that for ACF with Iodine (0.8 g/g).

4.5. AC/N_2

The adsorption characteristics of beads AC as an adsorbent and nitrogen as an adsorbate were introduced by Shen et al. [52]. Adsorption equilibrium for N_2 was measured at different temperatures and pressures. The highest adsorption capacity was 0.00756 g/g at 30 °C adsorption temperature and 100 kPa adsorption pressure. The isosteric heat magnitude was also determined to be 17.5 kJ/mol.

4.6. AC/diethyl ether

Granular AC and diethyl ether was introduced as an adsorption pair by Al-Ghouti et al. [53]. The normal Boiling temperature of diethyl ether ($(C_2H_5)_2O$) is 34.45 °C. The isosteric heat of the pair was found to be 45.84 kJ/mol and the time of equilibrium adsorption was ranged from 45 to 20 min as adsorption temperature was varied from 26 to 50 °C. Experimentally the adsorption capacity of the diethyl ether on AC at 26, 35, and 50 °C were 1.18, 1.63, and 1.39 mg/g, respectively at 10 kPa.

4.7. AC/R134a

The adsorption characteristics of activated carbon and R134a (1,1,1,2-tetrafluoroethane $C_2H_2F_4$) had been widely researched theoretically and experimentally by many researchers [54–56]. Using Maxsorb III as an adsorbent, the minimum isosteric heat for the pair was estimated to be about 21 kJ/mol. The maximum capacity for AC of R134a was 2 g/g at 30 °C isotherms adsorption at a pressure of 800 kPa. At 25 °C the time of adsorption was estimated to be 1200 s. The normal boiling temperature of R134a is −26.55 °C and the molecular weight is 102.03.

4.8. AC/R507A

Maxsorb III labeled MSC-30 and 99.99% pure R507A (1,1,1-trifluoroethane $C_2H_3F_3$) was used as an adsorption pair. The R507a is R125 and R134a in a fraction weight of 50% to 50% and its normal boiling point is −47.1 °C. When the isotherms adsorption temperature was 20 °C, the Maxsorb III adsorbed R507A as high as 1.3 g/g within an adsorption time interval of 1100 s [55].

4.9. AC/n-butane

The adsorption isotherms of n-butane (C_4H_{10} normal boiling point is −0.55 °C) on pitch based AC (Maxsorb III) at temperatures ranging from 25 to 55 °C and at different equilibrium pressures between 20 and 300 kPa have been experimentally measured. The isosteric heat of n-butane on Maxsorb III was 406 kJ/kg at loading of 0.7 g/g. The derived monolayer capacity of Maxsorb III/n-butane pair had been measured as 0.8 g/g with an adsorption temperature of 35 °C and 232.34 kPa. The time of adsorption at 25 °C was about 1400 s [57].

4.10. AC/CO_2

The adsorption characteristics and kinetics of AC/CO_2 pair was studied experimentally by Shen et al. [52]. Adsorption equilibrium for CO_2 was measured at different temperatures and pressures. The highest adsorption capacity was 0.0844 g/g at 30 °C and 100 kPa. The isosteric heat magnitude was also determined to be 23.17 kJ/mol.

Hines et al. [58], also studied the adsorption characteristics of Maxsorb AC with CO_2. The adsorption capacity was 1.135 g/g at 25 °C and 4586 kPa. The isosteric heat was determined to be 16.2 kJ/mol.

5. Discussion

Table 2 introduces the characteristics of the reviewed new adsorption pairs. The table shows that there are many of the new adsorption pairs which should be used in adsorption cooling systems and investigate its performances. It is clear from the table that there are new adsorption pairs have a relatively high adsorption capacity with a low evaporation temperature. Among of these pairs AC/R134a has a relatively high adsorption capacity and low evaporation temperature (−26.55 °C). But the problem with R134a that it has a high global worming potential value (1300). The lowest adsorption capacity is for the pair of AC/N_2 however, the highest adsorption capacity if for the pair of AC/R134a. Although the AC/N_2 has a relatively low adsorption capacity; it has the lowest boiling temperature (−195.8 °C) which means it will be good to be used in refrigeration applications. AC/diethyl ether has a relatively high adsorption capacity of about 1.63 but it has the disadvantages of working at vacuum pressure and a relatively high boiling temperature of about 34 °C.

6. Conclusions

The study reviewed the adsorbent–refrigerant pairs used in cooling applications and the new pairs for potential applications. A comparison between the working conditions for existing adsorption cooling system was introduced. The maximum COP achieved by the adsorption cooling system is 0.83. The adsorption cooling system employing silica gel and chloride composites/water pair has the highest COP value. The system of zeolite with water pair has the lowest value of the COP. The lowest evaporation temperature is with metal hydrides/hydrogen which is as low as −50 °C. According to the driving temperature, silica gel and chloride composites/methanol pair has the lowest required driving temperature. However; zeolite/water pair requires the highest driving temperature up to 350 °C.

Also the characteristics of the new adsorption pairs are conducted. Many new pairs show a promising future for cooling applications. AC/R134a pair shows the highest adsorption capacity of about 2 kg/kg. Nitrogen as a refrigerant shows a good adsorption characteristics with ACF as it can be used for cryocooling applications. From the study it could be concluded that there are many new adsorption pairs which should be employed and tested in adsorption cooling systems in the next few years. It can be concluded from the present study that the adsorption cooling systems still require significant research and development activities and can be promising over traditional cooling systems.

References

[1] Hussein Watheq Khalil Said, Solar Energy Refrigeration by Liquid–Solid Adsorption Technique, MSC thesis, An-Najah National University, 2008.
[2] Pridasawas Wimolsiri, Solar-Driven Refrigeration Systems with Focus on the Ejector Cycle, Doctoral Thesis, Royal Institute of Technology, KTH, Denmark, 2006.
[3] Yeo THC, Tan IAW, Abdullah MO. Development of adsorption air-conditioning technology using modified activated carbon—a review. Renewable Sustainable Energy Review 2012;16:3355–63.
[4] Plank R, Kuprianoff J. Die Klein Käeltemaschine. Berlin: Springer; 1960.
[5] Askalany AA, Salem M, Ismael IM, Ali AHH, Morsy MG. A review on adsorption cooling systems with adsorbent carbon. Renewable Sustainable Energy Review 2012;16:493–500.
[6] Lemmini Fatiha, Errougani Abdelmoussehel. Technical note experimentation of a solar adsorption refrigerator in Morocco. Renewable Energy 2007;32: 2629–41.
[7] Alghoul MA, Sulaiman MY, Azmi BZ, Wahab MAbd. Advances on multipurpose solar adsorption systems for domestic refrigeration and water heating. Applied Thermal Engineering 2007;27:813–22.
[8] Wang DC, Li YH, Li D, Xia YZ, Zhang JP. A review on adsorption refrigeration technology and adsorption deterioration in physical adsorption systems. Renewable Sustainable Energy Review 2010;14:344–53.
[9] Critoph RE. Evaluation of alternative refrigerant–adsorbent pairs for refrigeration cycles. Applied Thermal Engineering 1996;16(11):891–900.
[10] Srivastava NC, Eames IW. A review of adsorbents and adsorbates in solid–vapour adsorption heat pump systems. Applied Thermal Engineering 1998;18:707–14.
[11] Wang LW, Wang RZ, Lu ZS, Chen CJ, Wang K, Wu JY. The performance of two adsorption ice making test units using activated carbon and a carbon composite as adsorbents. Carbon 2006;44:2671–80.
[12] Tamainot-Telto Z, Critoph RE. Adsorption refrigerator using monolithic carbon–ammonia pair. International Journal of Refrigeration 1997;20(2): 146–55.
[13] Tamainot-Telto Z, Metcalf SJ, Critoph RE, Zhong Y, Thorpe R. Carbon–ammonia pairs for adsorption refrigeration applications: ice making, air conditioning and heat pumping. International Journal of Refrigeration 2009;32:1212–29.
[14] Critoph RE, Metcalf SJ. Specific cooling power intensification limits in ammonia–carbon adsorption refrigeration systems. Applied Thermal Engineering 2004;24: 661–78.
[15] Metcalf SJ, Critoph RE, Tamainot-Telto Z. Optimal cycle selection in carbon–ammonia adsorption cycles. International Journal of Refrigeration 2012;35:571–80.
[16] HU ERIC J. A study of thermal decomposition of methanol in solar powered adsorption refrigeration systems. Solar Energy 1998;52(5):325–9.
[17] El-Sharkawy II, Hassan M, Saha BB, Koyama S, Nasr MM. Study on adsorption of methanol onto carbon based adsorbents. International Journal of Refrigeration 2009;32:1579–86.

[18] Wang LW, Wu JY, Wang RZ, Xu YX, Wang SG, Li XR. Study of the performance of activated carbon–methanol adsorption systems concerning heat and mass transfer. Applied Thermal Engineering 2003;23:1605–17.
[19] Saha El-Sharkawy BB, Koyama S, He J, Ng KC, Yap C. Experimental investigation on activated carbon–ethanol pair for solar powered adsorption cooling applications. International Journal of Refrigeration 2008;31:1407–13.
[20] Saha BB, El-Sharkawy II, Chakraborty A, Koyama S. Study on an activated carbon fibereethanol adsorption chiller: part I e system description and modeling. International Journal of Refrigeration 2007;30:86–95.
[21] Saha BB, El-Sharkawy II, Chakraborty A, Koyama S. Study on an activated carbon fibereethanol adsorption chiller: part II e performance evaluation. International Journal of Refrigeration 2007;30:96–102.
[22] Wang LW, Wang RZ, Oliveira RG. A review on adsorption working pairs for refrigeration. Renewable Sustainable Energy Review 2009;13:518–34.
[23] Chen CJ, Wang RZ, Xia ZZ, Kiplagat JK, Lu ZS. Study on a compact silica gel–water adsorption chiller without vacuum valves: design and experimental study. Appl Energy 2010;87:2673–81.
[24] Grisel Ruud JH, Smeding Simon F, de Boer Robert. Waste heat driven silica gel/water adsorption cooling in trigeneration. Applied Thermal Engineering 2010;30:1039–46.
[25] Wang Dechang, Zhang Jipeng, Xia Yanzhi, Han Yanpei, Wang Shuwei. Investigation of adsorption performance deterioration in silica gel-water adsorption refrigeration. Energy Conversion Management 2012;58:157–62.
[26] Solmus Ismail, Yamal Cemil, Kaftanoglu Bilgin, Baker Derek, Çaglar Ahmet. Adsorption properties of a natural zeolite–water pair for use in adsorption cooling cycles. Applied Energy 2010;87:2062–7.
[27] Wang DC, Xia ZZ, Wu JY. Design and performance prediction of a novel zeolite–water adsorption air conditioner. Energy Conversion Management 2006;47:590–610.
[28] Vasta Salvatore, Freni Angelo, Sapienza Alessio, Costa Fabio, Restuccia Giovanni. Development and lab-test of a mobile adsorption air-conditioner. International Journal of Refrigeration 2012;35:701–8.
[29] Rivera C, Pilatowsky I, Méndez E, Rivera W. Experimental study of a thermo-chemical refrigerator using the barium chloride–ammonia reaction. International Journal of Hydrogen Energy 2007;32:3154–8.
[30] Duenas C, Pilatowskya I, Romeroa RJ, Oskama A, Finck AP. Dynamic study of the thermal behavior of solar thermochemical refrigerator: barium chloride–ammonia for ice production. Solar Energy Materials and Solar Cells 2001;70: 401–13.
[31] Kim KJ, Feldman Jr KT, Lloydt G, Razanit A. Compressor-driven metal-hydride heat pumps. Applied Thermal Engineering 1997;17(6):551–60.
[32] Willers E, Groll M. Evaluation of metal hydride machines for heat pumping and cooling applications. International Journal of Refrigeration 1999;22: 47–58.
[33] Sakintuna Billur, Lamari-Darkrim Farida, Hirscher Michael. Metal hydride materials for solid hydrogen storage: a review. International Journal of Hydrogen Energy 2007;32:1121–40.
[34] Kato Y, Yamashita Norimichi, Kobayashi Kei, Yoshizawa Yoshio. Kinetic study of the hydrogen of magnesium oxide for a chemical heat pump. Applied Thermal Engineering 1996;16(I1):853–62.
[35] Kato Y, Sasaki Y, Yoshizawa Y. Magnesium oxide/water chemical heat pump to enhance energy utilization of a cogeneration system. Energy 2005;30: 2144–55.
[36] Lee Chan Ho, Park Seong Ho, Choi Seung Hoon, Kim Young Seok, Kim Sung Hyun. Characteristics of non-uniform reaction blocks for chemical heat pump. Chemical Engineering Science 2005;60:1401–9.
[37] Han Jong Hun, Lee Kun-Hong. Gas permeability of expanded graphite–metallic salt composite. Applied Thermal Engineering 2001;21:453–63.
[38] Aristov YuI, Restuccia G, Cacciola G, Parmon VN. A family of new working materials for solid sorption air conditioning systems. Applied Thermal Engineering 2002;22:191–204.
[39] Gordeeva Larisa G, Grekova Alexandra D, Krieger Tamara A, Aristov Yuriy I. Adsorption properties of composite materials (LiCl+LiBr)/silica. Microporous Mesoporous Matter 2009;126:262–7.
[40] Maggio G, Gordeeva LG, Freni A, Aristov YuI, Santori G, Polonara F, et al. Simulation of a solid sorption ice-maker based on the novel composite sorbent lithium chloride in silica gel pores. Applied Thermal Engineering 2009;29:1714–20.
[41] Oliveira RG, Wang RZ, Wang C. Evaluation of the cooling performance of a consolidated expanded graphite calcium chloride reactive bed for chemisorption icemaker. International Journal of Refrigeration 2007;30:103–12.
[42] Veselovskaya JV, Tokarev MM, Aristov YuI. Novel ammonia sorbents porous matrix modified by active salt for adsorptive heat transformation 1. Barium chloride in various matrices. Applied Thermal Engineering 2010;30:584–9.
[43] Veselovskaya JV, Critoph RE, Thorpe RN, Metcalf S, Tokarev MM, Aristov YuI. Novel ammonia sorbents porous matrix modified by active salt for adsorptive heat transformation: 3. Testing of $BaCl_2$/vermiculite composite in a lab-scale adsorption chiller. Applied Thermal Engineering 2010;30:1188–92.
[44] Grekova Alexandra D, Veselovskaya Janna V, Tokarev Mikhail M, Gordeeva Larisa G. Novel ammonia sorbents porous matrix modified by active salt for adsorptive heat transformation: 5. Designing the composite adsorbent for ice makers. Applied Thermal Engineering 2012;37:80–6.
[45] Wang LW, Wang RZ, Lu ZS, Chen CJ, Wang K, Wu JY. The performance of two adsorption ice making test units using activated carbon and a carbon composite as adsorbents. Carbon 2006;44:2671–80.
[46] Hu Peng, Yao Juan-Juan, Chen Ze-Shao. Analysis for composite zeolite/foam aluminum–water mass recovery adsorption refrigeration system driven by engine exhaust heat. Journal of Energy Conversion and Management 2009;50:255–61.
[47] Huang Chen-Chia, Chen Hsiu-Mei, Chen Chien-Hung. Hydrogen adsorption on modified activated carbon. International Journal of Hydrogen Energy 2010;35:2777–80.
[48] Kojima Yoshitsugu, Kawai Yasuaki, Koiwai Akihiko, Suzuki Nobuaki, Haga Tetsuya, Hioki Tatsumi, et al. Hydrogen adsorption and desorption by carbon materials. Journal of Alloys and Compounds 2006;421:204–8.
[49] Ridha Firas N, Webley Paul A. Entropic effects and isosteric heats of nitrogen and carbon dioxide adsorption on chabazite zeolites. Microporous Mesoporous Materials 2010;132:22–30.
[50] Zhong Y, Critoph RE, Thorpe R. Evaluation of the performance of solid sorption refrigeration systems using carbon dioxide as refrigerant. Applied Thermal Engineering 2006;26:1807–11.
[51] Yang Cheol-Min, Kaneko Katsumi. Adsorption properties of iodine-doped activated carbon fiber. Journal of Colloid and Interface Science 2002;246: 34–9.
[52] Shen Chunzhi, Grande Carlos A, Li Ping, Yu Jianguo, Rodrigues Alirio E. Adsorption equilibria and kinetics of CO_2 and N_2 on activated carbon beads. Chemical Engineering Journal 2010;160:398–407.
[53] Al-Ghoutia Mohammad A, Yousef Ibrahim, Ahmad Rafat, Ghraira Ayoup M, Al-Maaitah Ayman A. Characterisation of diethyl ether adsorption on activated carbon using a novel adsorption refrigerator. Chemical Engineering Journal 2010;162:234–41.
[54] Saha Bidyut B, Habib Khairul, El-Sharkawy Ibrahim I, Koyama Shigeru. Adsorption characteristics and heat of adsorption measurements of R-134a on activated. International Journal of Refrigeration 2009;32:1563–9.
[55] Habib Khairul, Saha Bidyut B, Rahman Kazi A, Chakraborty Anutosh, Koyama Shigeru, Ng Kim Choon. Experimental study on adsorption kinetics of activated carbon/R134a and activated carbon/R507A pairs. International Journal of Refrigeration 2010;33:706–13.
[56] Askalany AA, Salem M, Ismael IM, Ali AHH, Morsy MG. Experimental study on adsorption–desorption characteristics of granular activated carbon/R134a pair. International Journal of Refrigeration 2012;35:494–8.
[57] Saha Bidyut Baran, Chakraborty Anutosh, Koyama Shigeru, Yoon Seong-Ho, Mochida Isao, Kumja M, et al. Isotherms and thermodynamics for the adsorption of n-butane on pitch based activated carbon. International Journal of Heat and Mass Transfer 2008;51:1582–9.
[58] Hines AL, Kuo SL, Dural NH. A new analytical isotherm equation for adsorption on heterogeneous adsorbents. Separation Science and Technology 1990;25(7–8):869–88.